Sensitivity of equivalent EDM to SMEFT

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IFIC (University of Valencia-CSIC)

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Based on M. Ardu, N. Valori: arXiv 2503.21920

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IFIC INSTITUT DE FÍSICA CORPUSCULAR
CSIC
VNIVERSITAT DE VALÈNCIA

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- Dark Matter
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New sources of CP violation are necessary!

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→ *P(CP)-odd interaction*

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→ *Indirect search for CP-odd NP*

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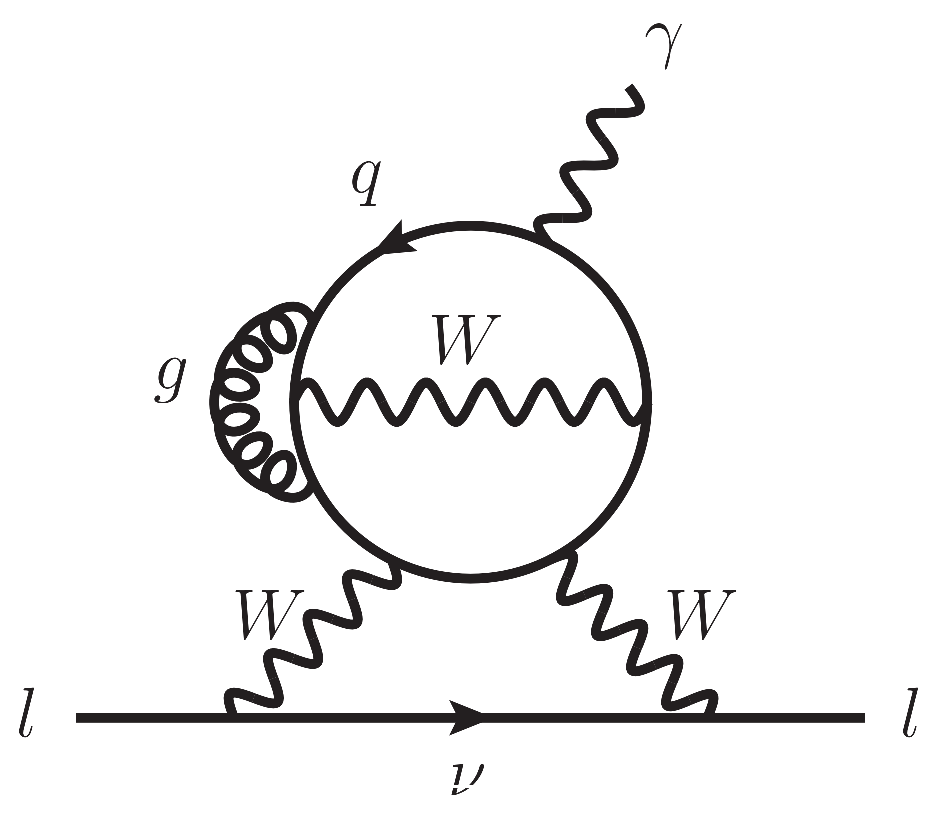
Extremely suppressed
In SM

CP-violation: Jarlskog invariant ($\mathcal{J}$)



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$$d_e \sim O(10^{-44})\, e \cdot cm$$

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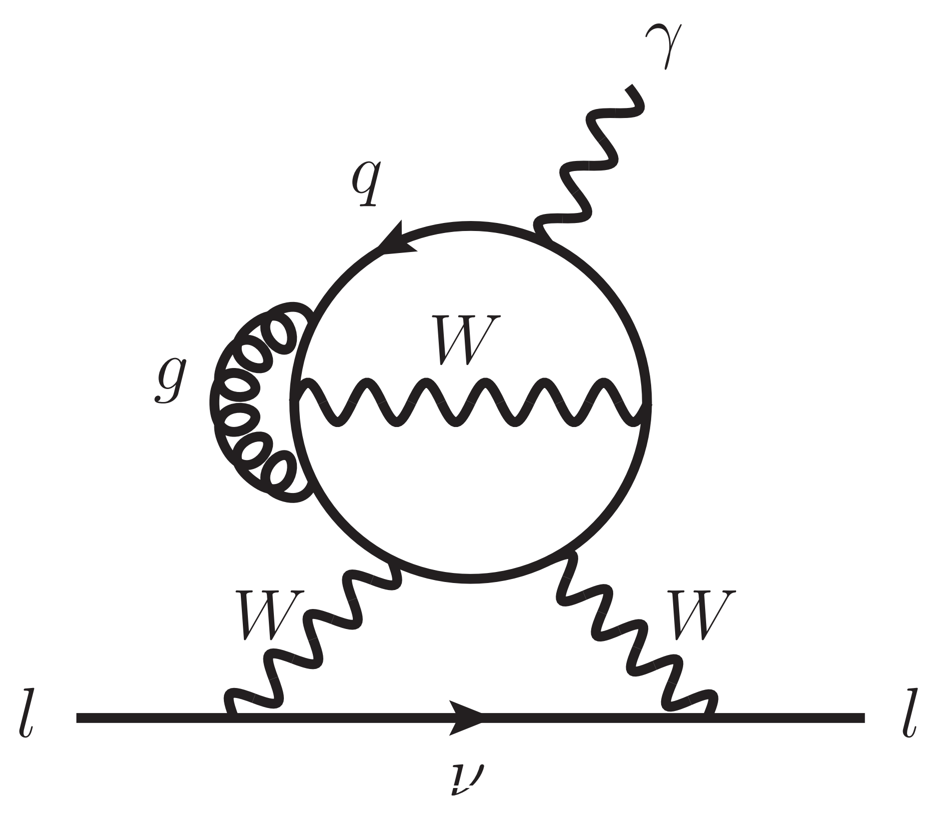

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Experiment	Current bound/Upcoming sensitivity
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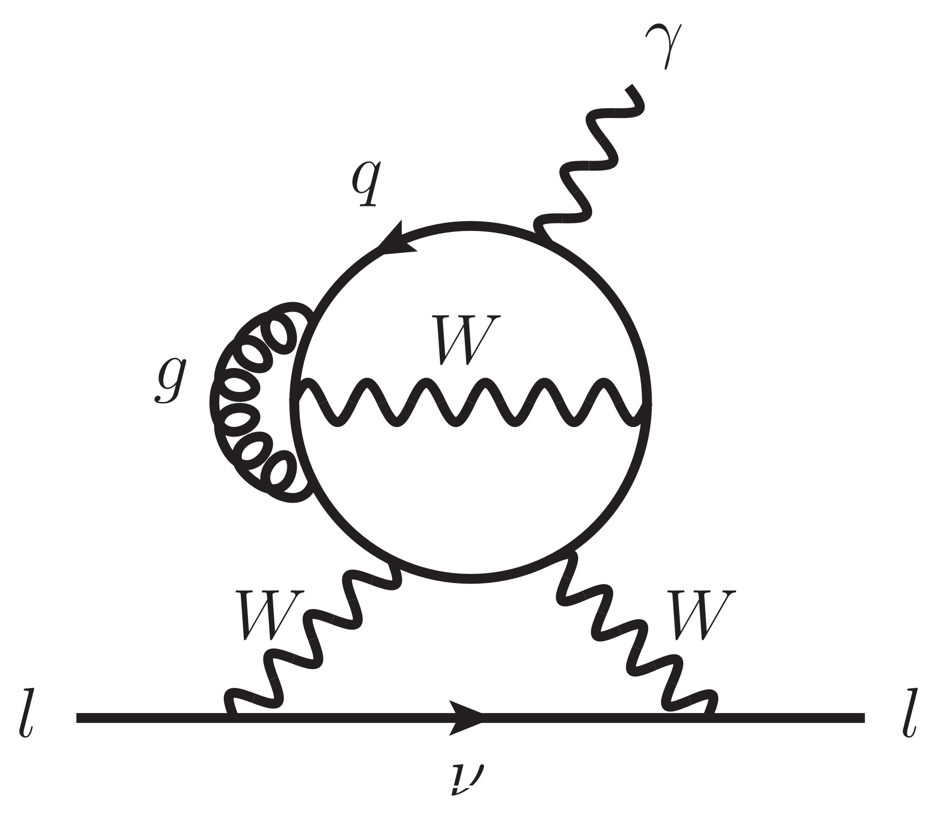

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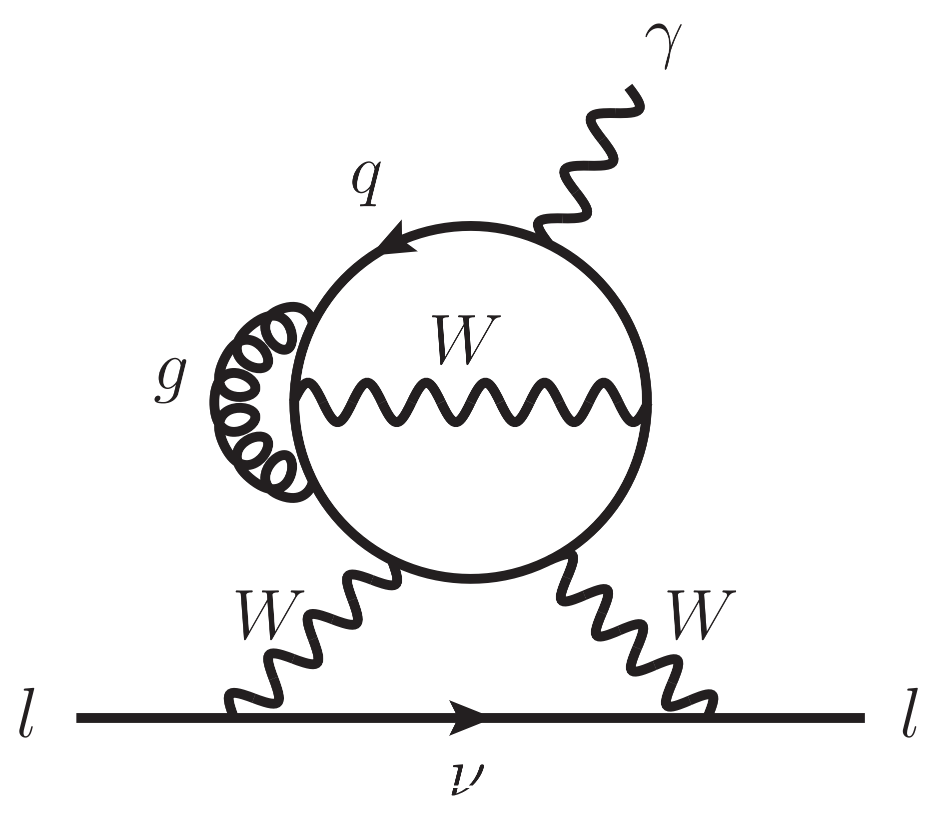

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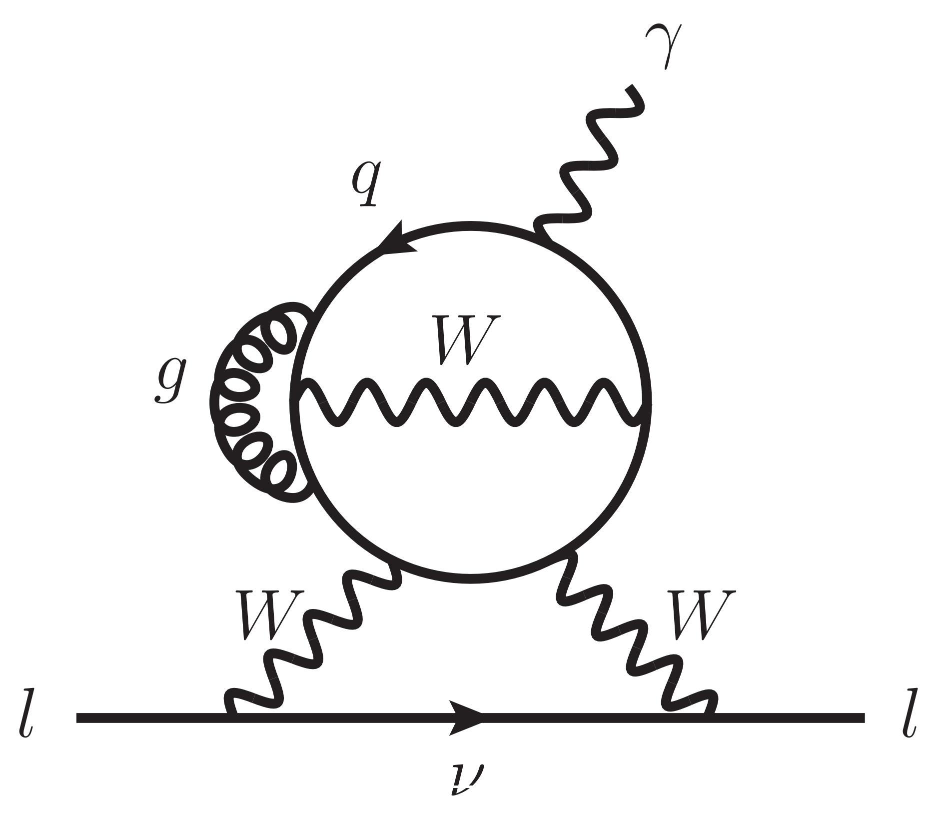

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Detection of an eEDM in the forthcoming years would be a clear evidence for NP

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Short distance?

SMEFT in a nutshell

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Ren. scale ⟵ μ

Long story short:

Running, mixing and matching across the various EFTs is such that the equiv. EDM is sensitive to a broad class of operators

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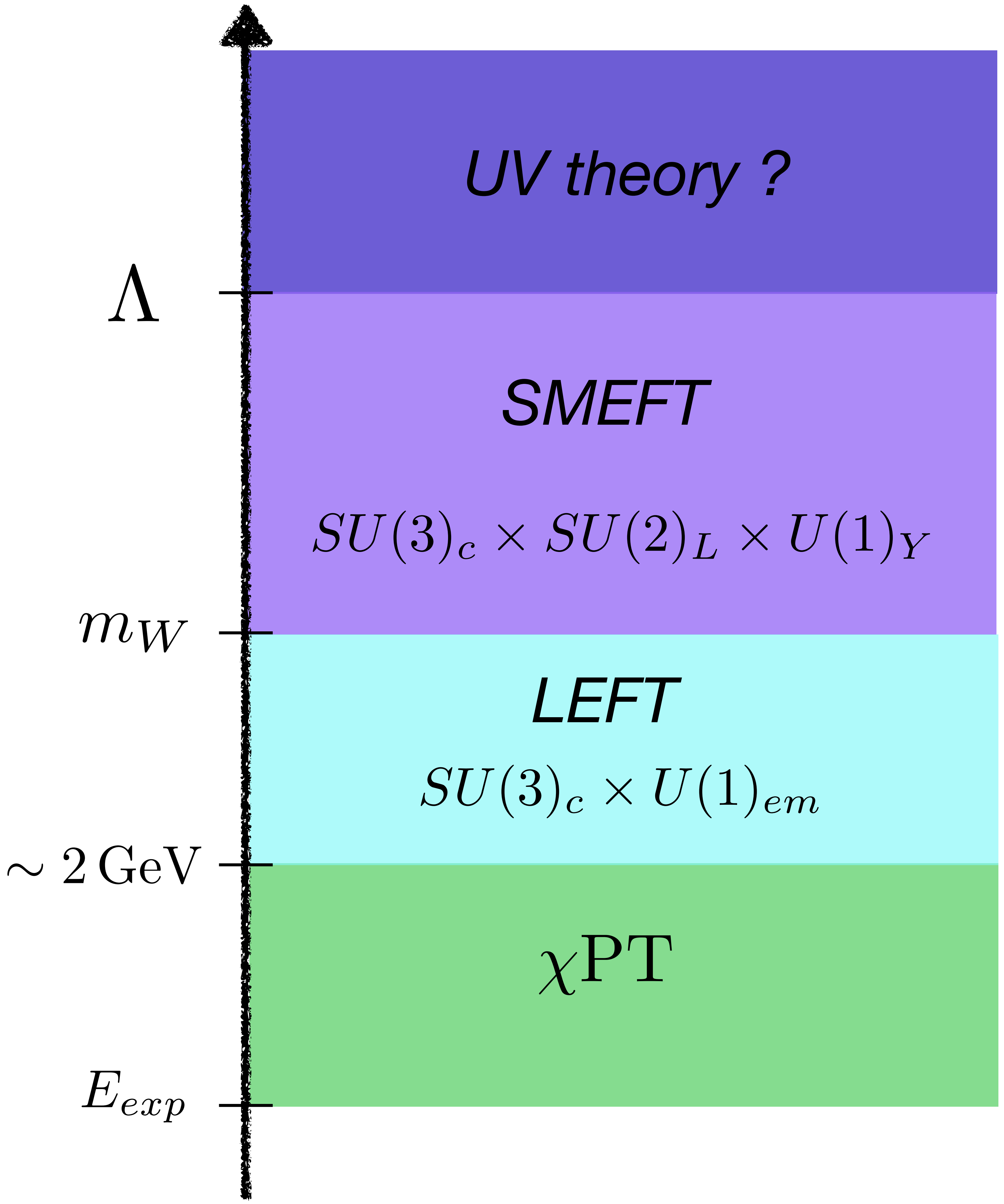

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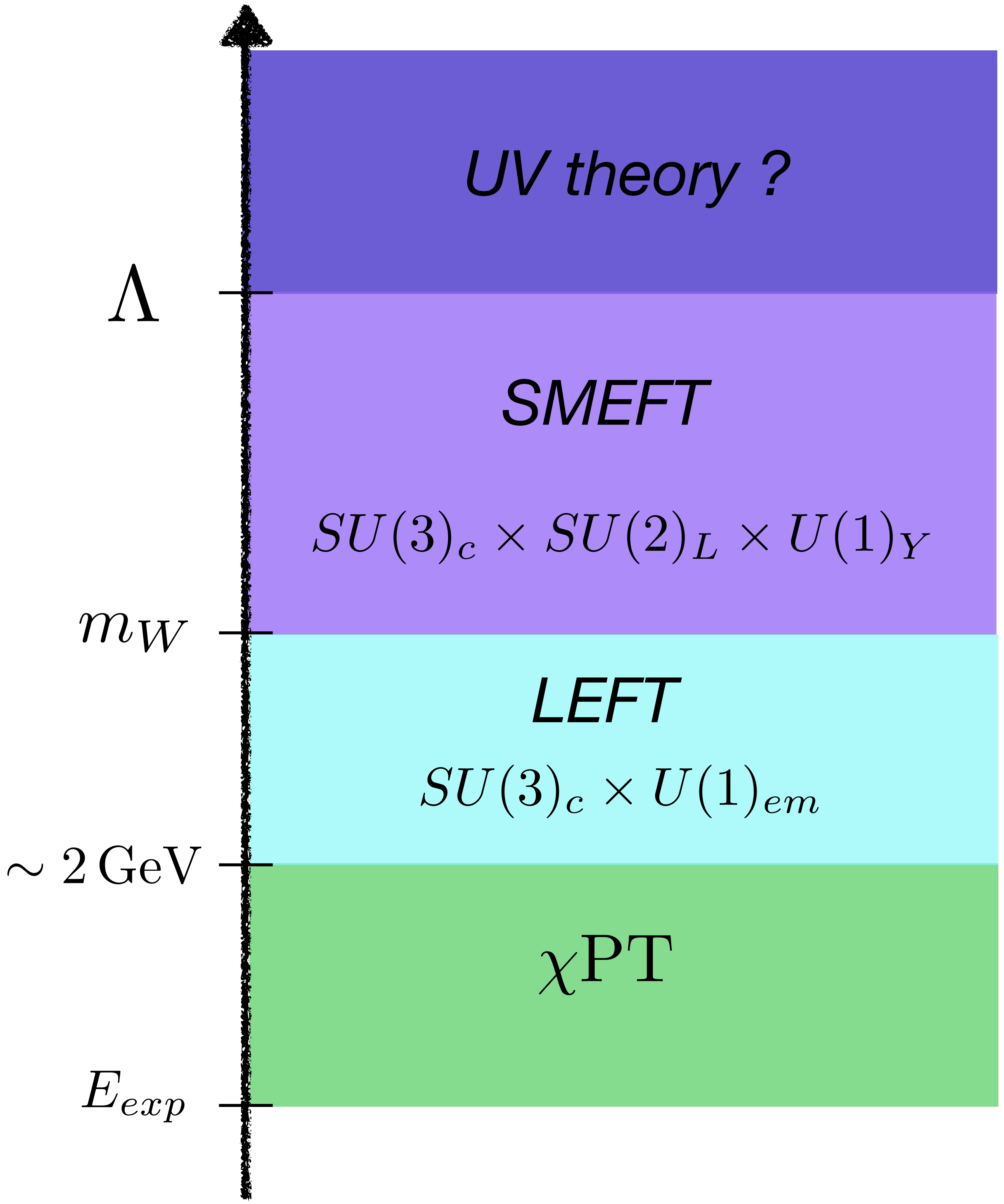

We fixed NP scale at 10 TeV

One operator at a time $O_i^{(n)}$

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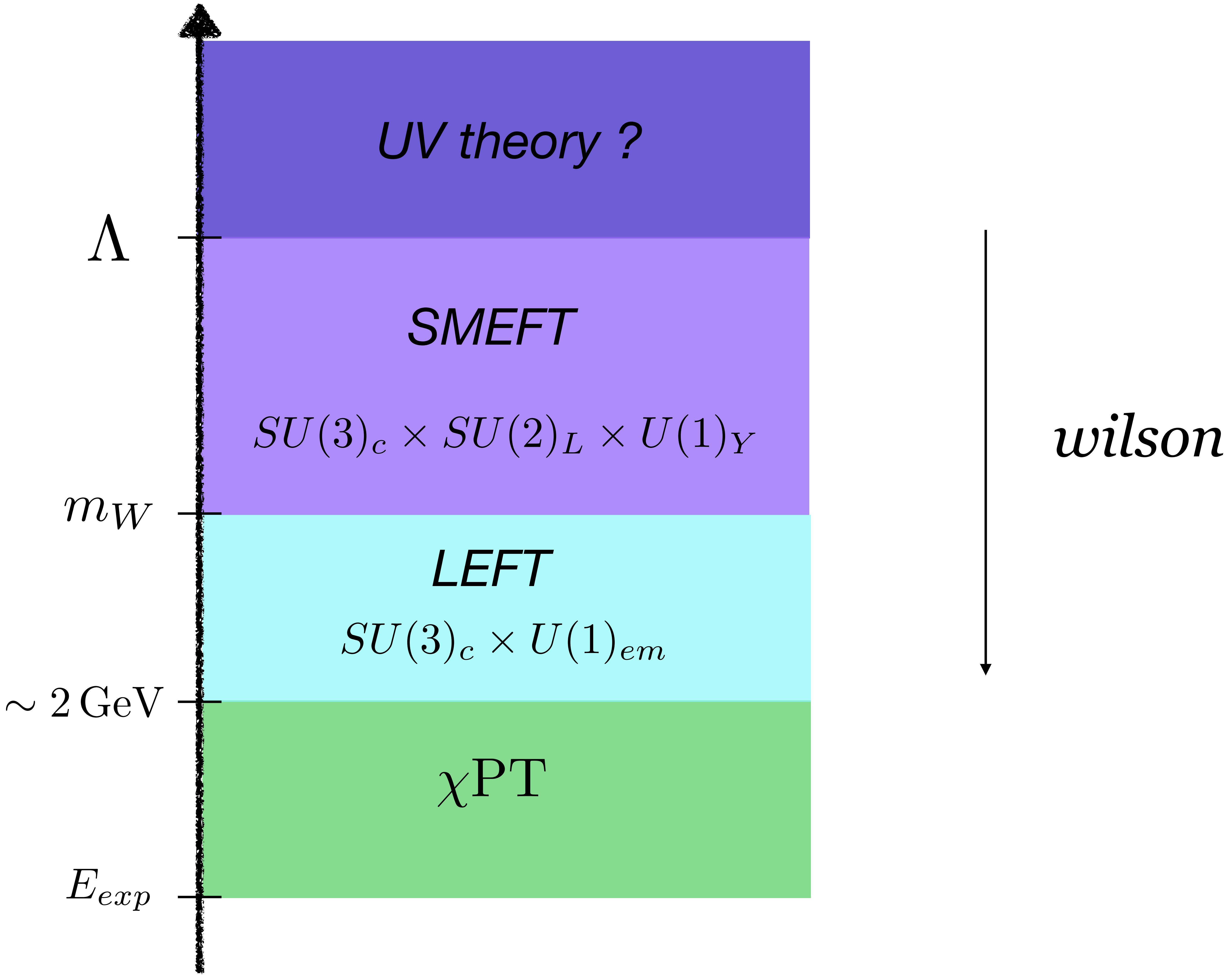

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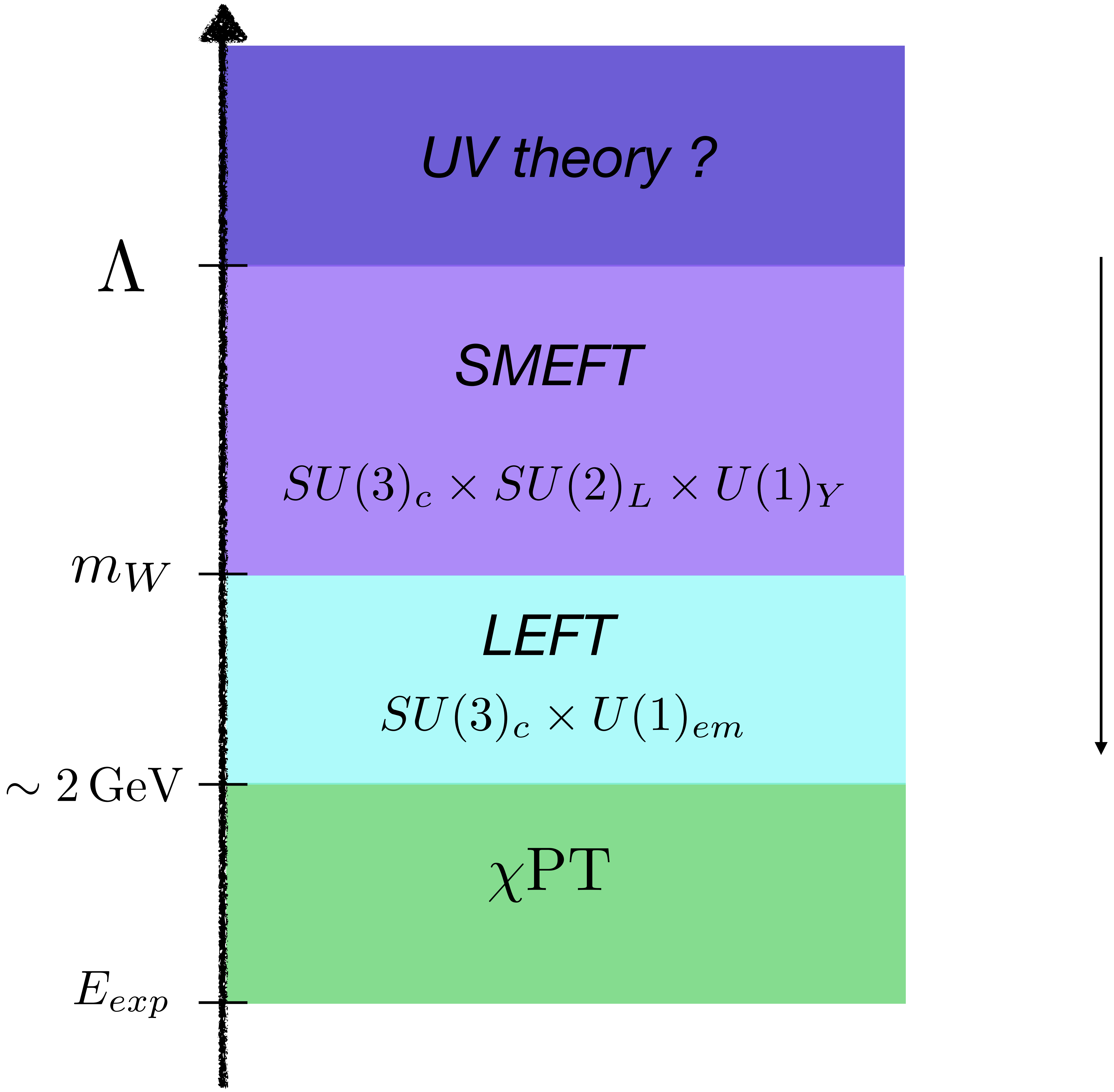

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wilson → Automated running and matching SMEFT-LEFT

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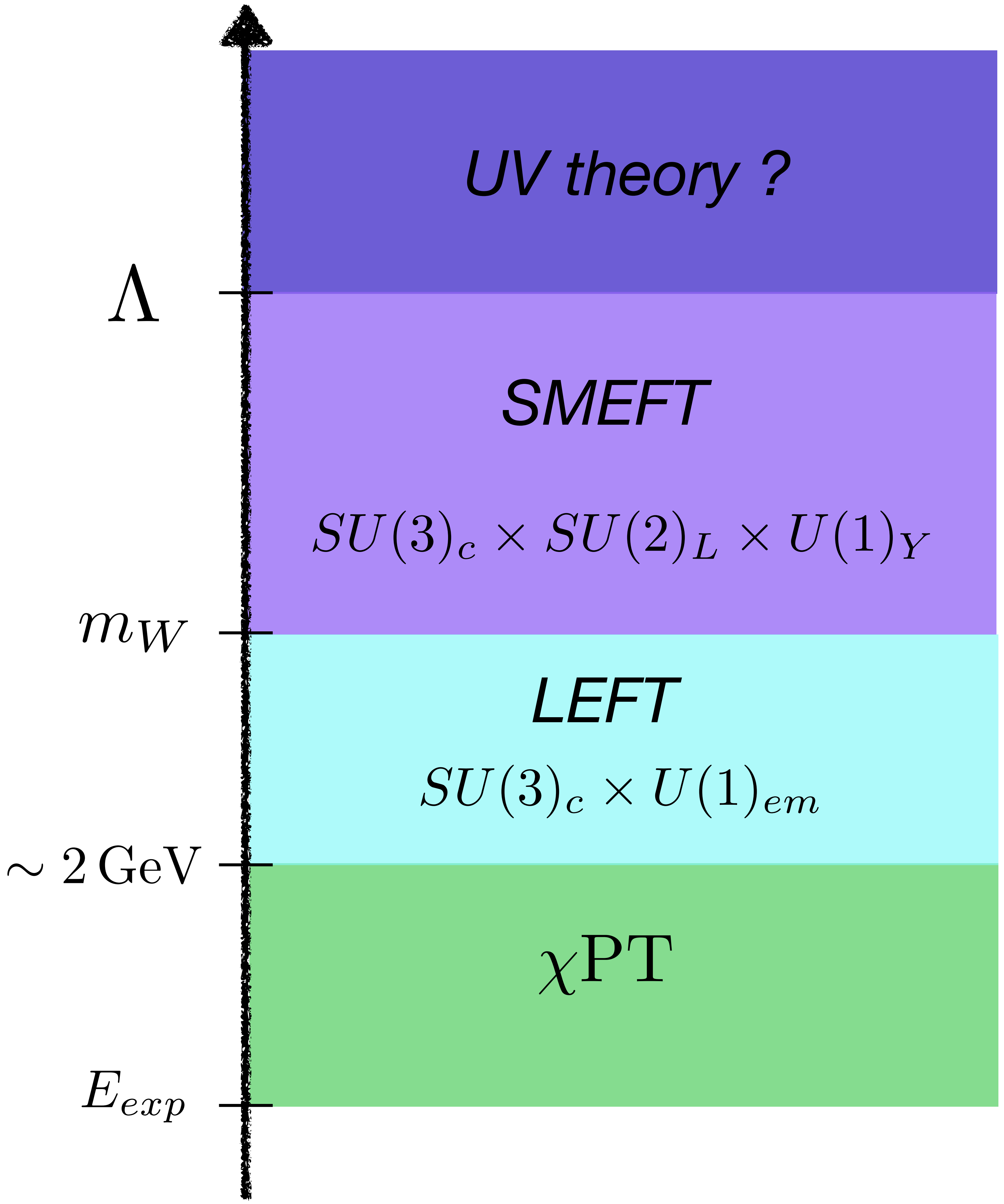

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$\downarrow$

wilson $\longrightarrow$ *Automated running and matching SMEFT-LEFT*

Matching
EFT + LQCD

[Hoferichter et al.,hep-ph/092301]

[P. M. Junnarkar et al.,hep-ph/114510]

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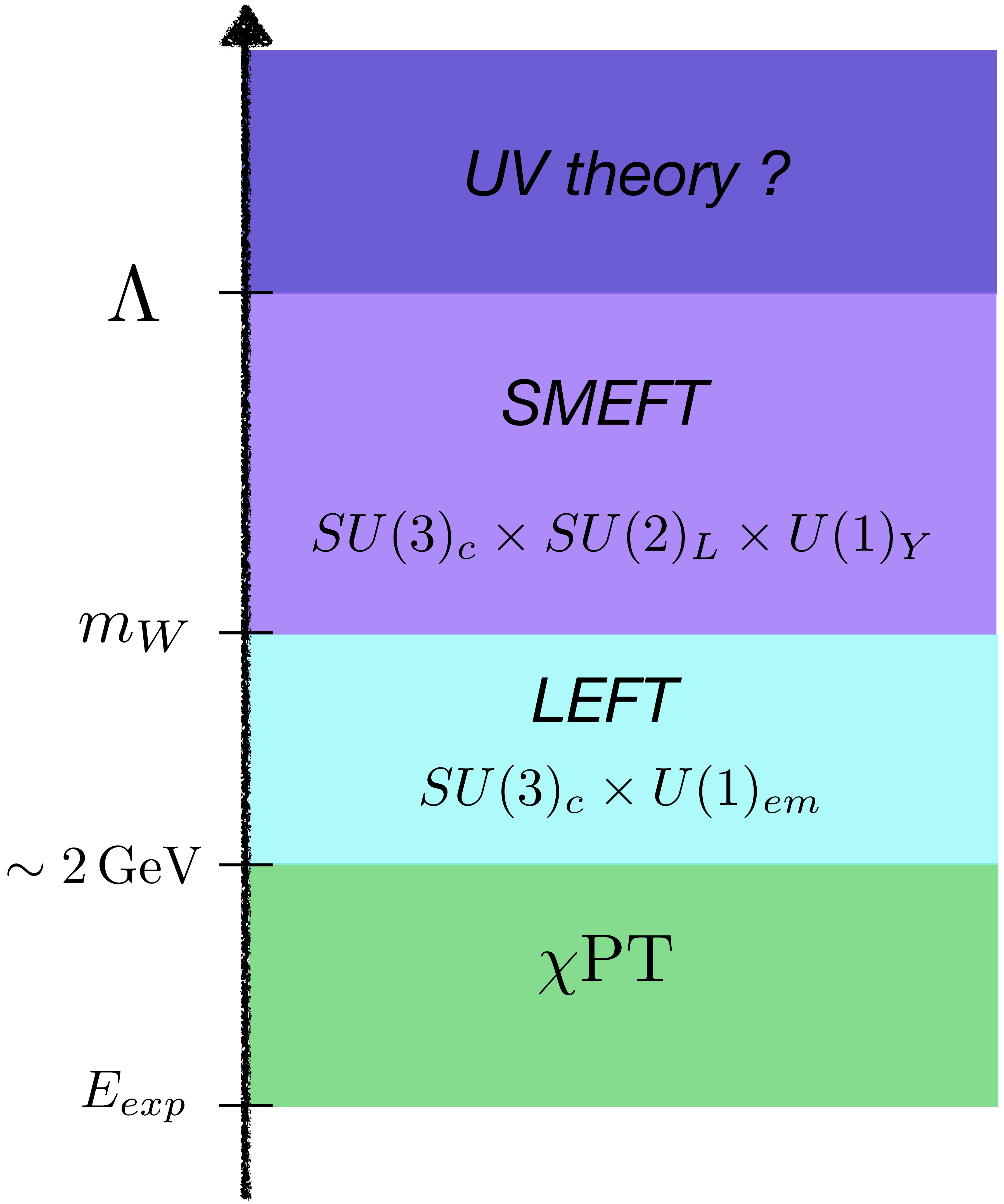

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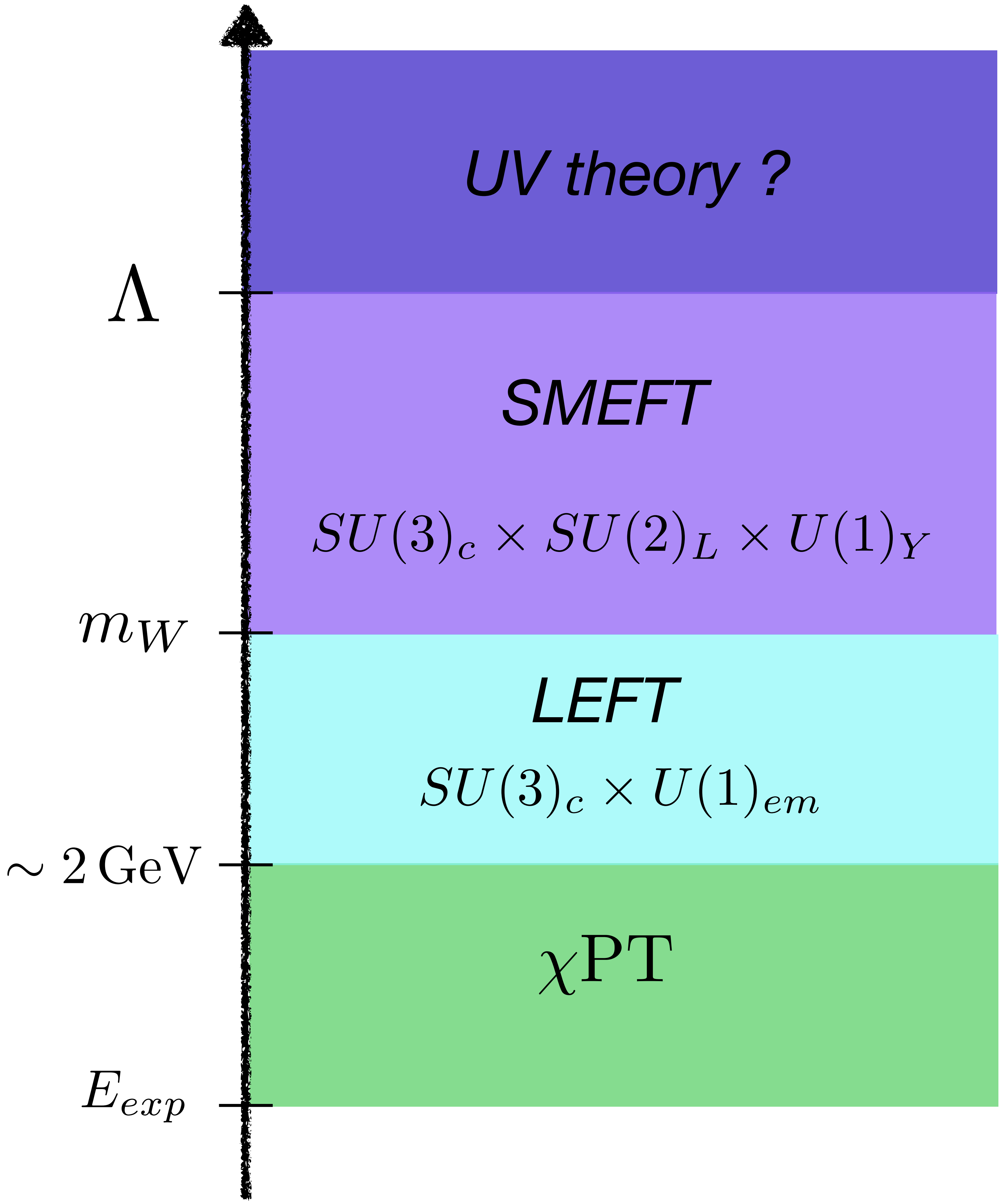

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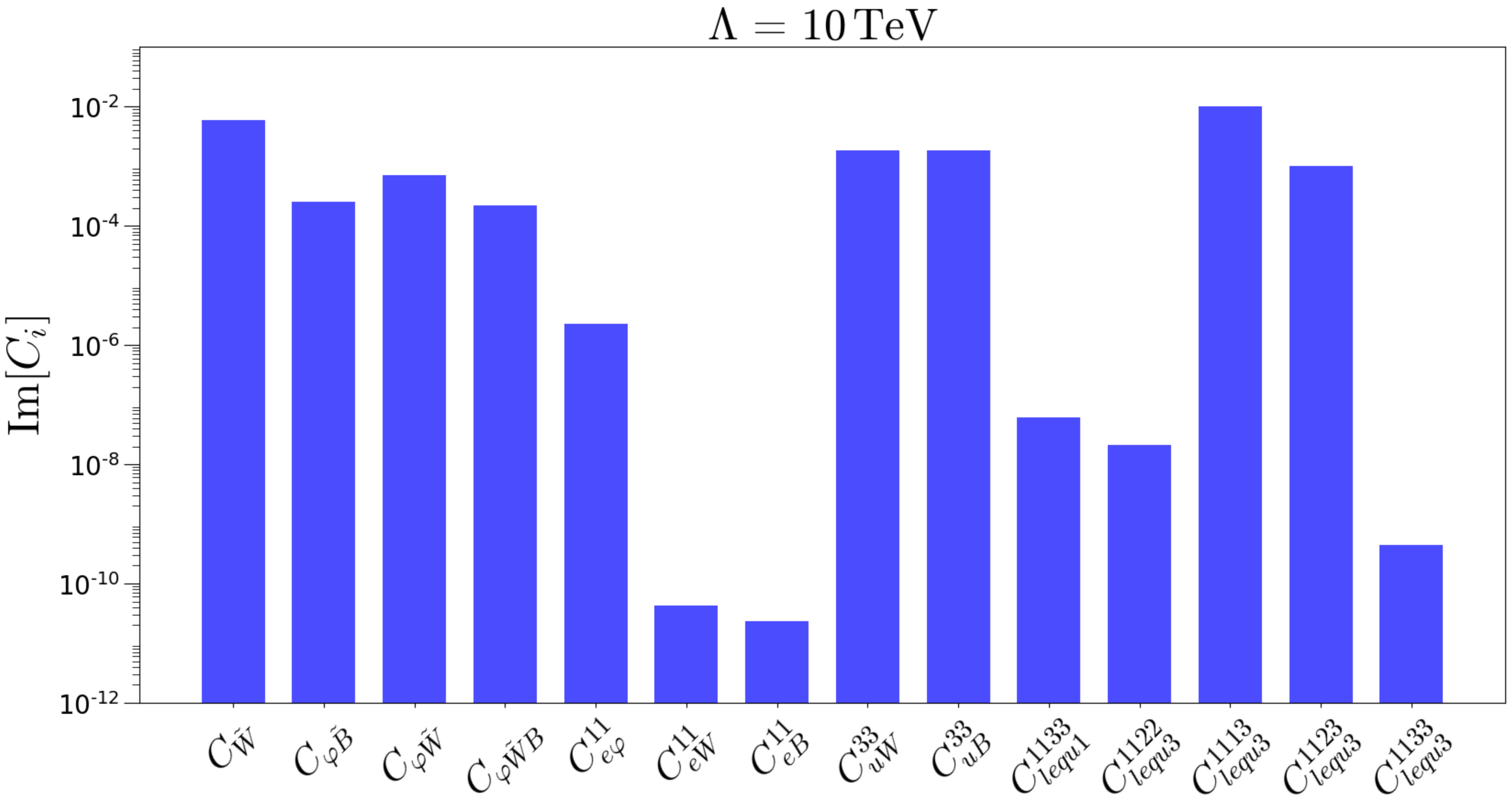

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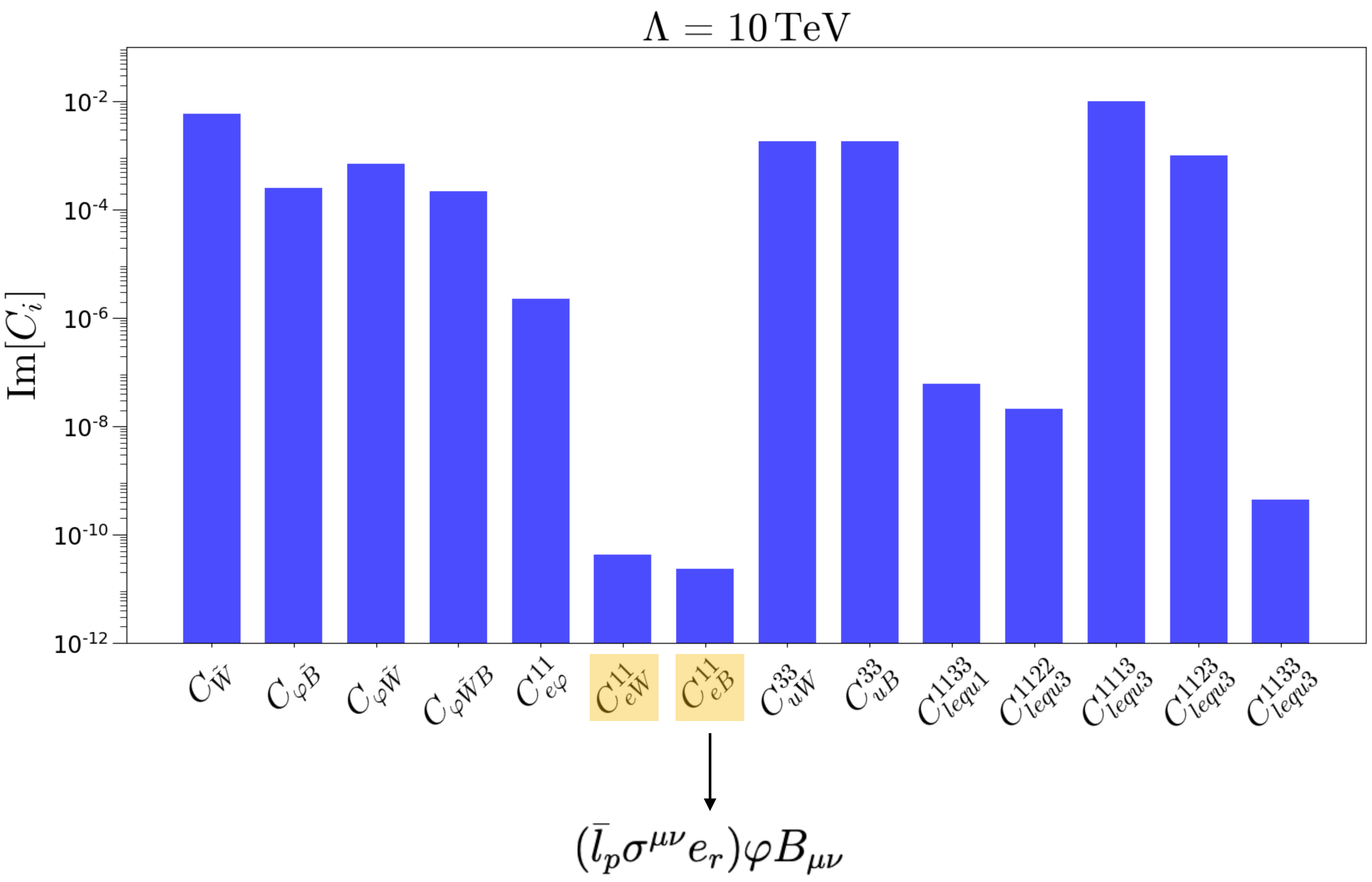


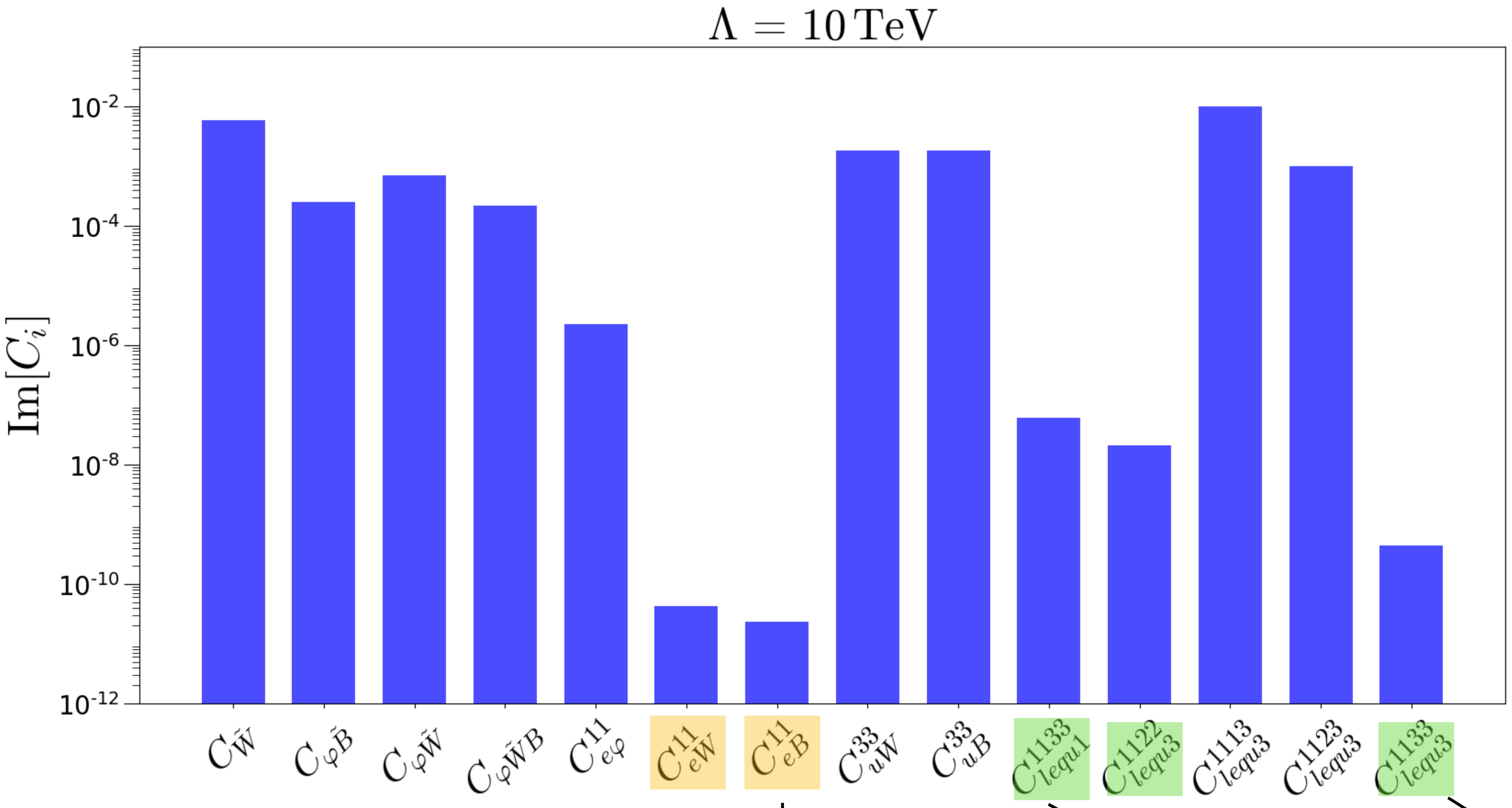
Largest effects from:

- Dipole operators $\psi^2 X \varphi$

Results I:

Large set of operators where $d^{\text{equiv.}} \sim d_e$

$$d^{\text{equiv.}}_{\text{HfF+}} < 4.1 \times 10^{-30}\ e \cdot cm$$



$(\bar{l}_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$

$(\bar{l}^j_p e_r)\varepsilon_{jk}(\bar{q}^k_s u_t)$

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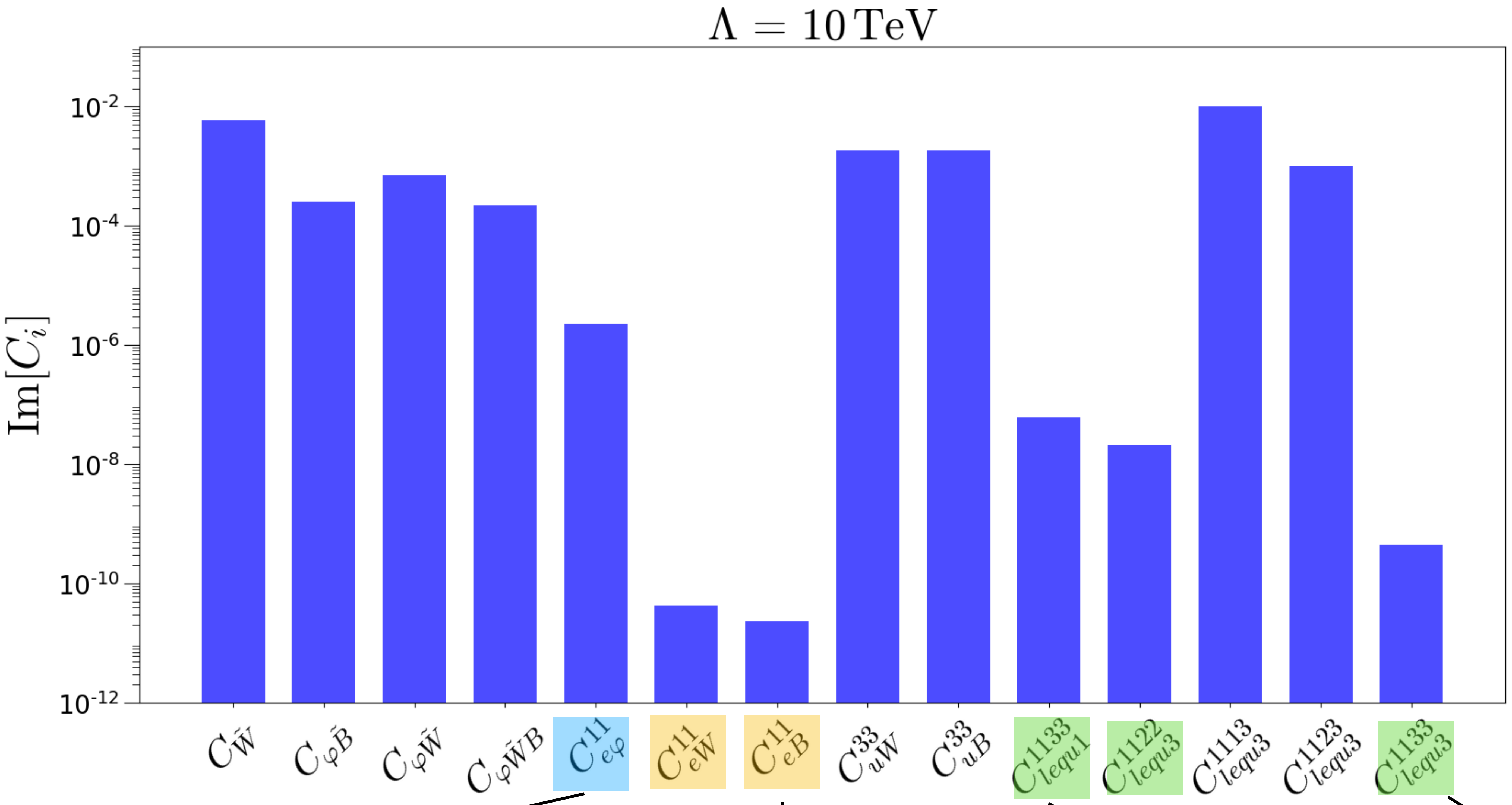

$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$

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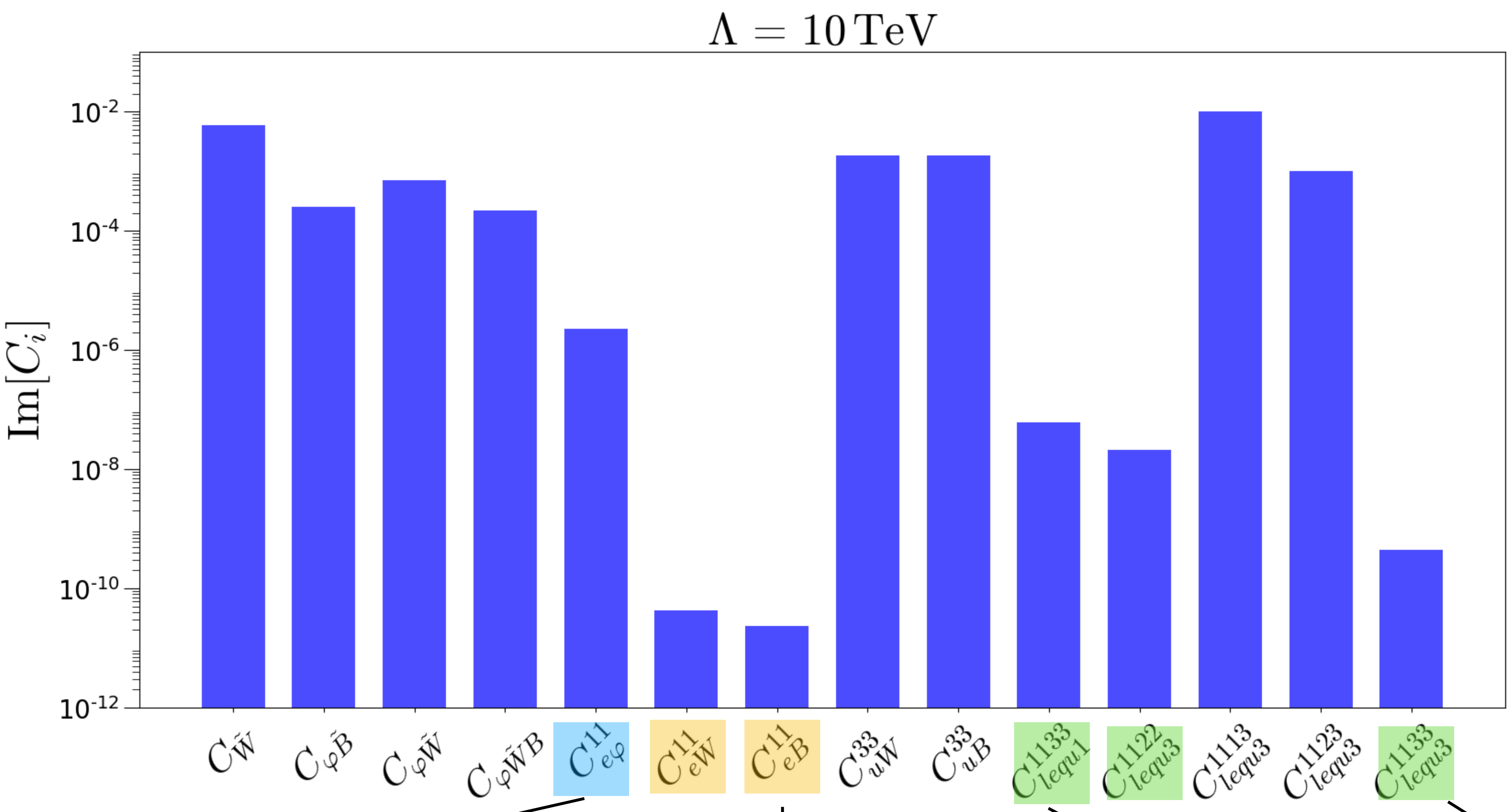

$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$ $(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$ $(\bar l^j_p e_r)\varepsilon_{jk}(\bar q^k_s u_t)$ $(\bar l^j_p \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q^k_s \sigma^{\mu\nu} u_t)$

Consistency with previous works

[Kley et al., 2109.15085]
[Panico et al., 1810.09413]

Largest effects from:

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- Mixing featuring heavy quarks $(\bar L R)(\bar L R)$
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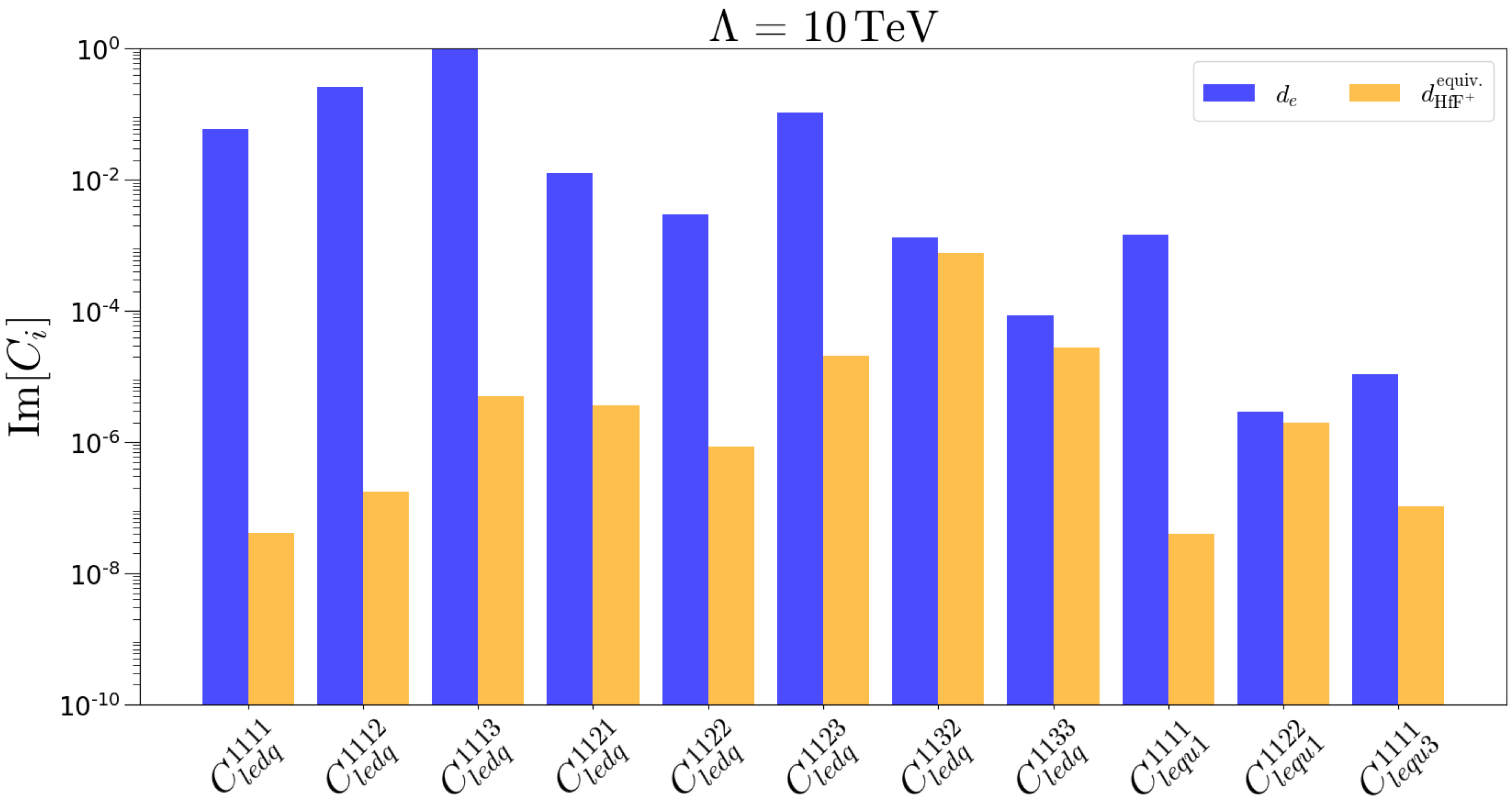

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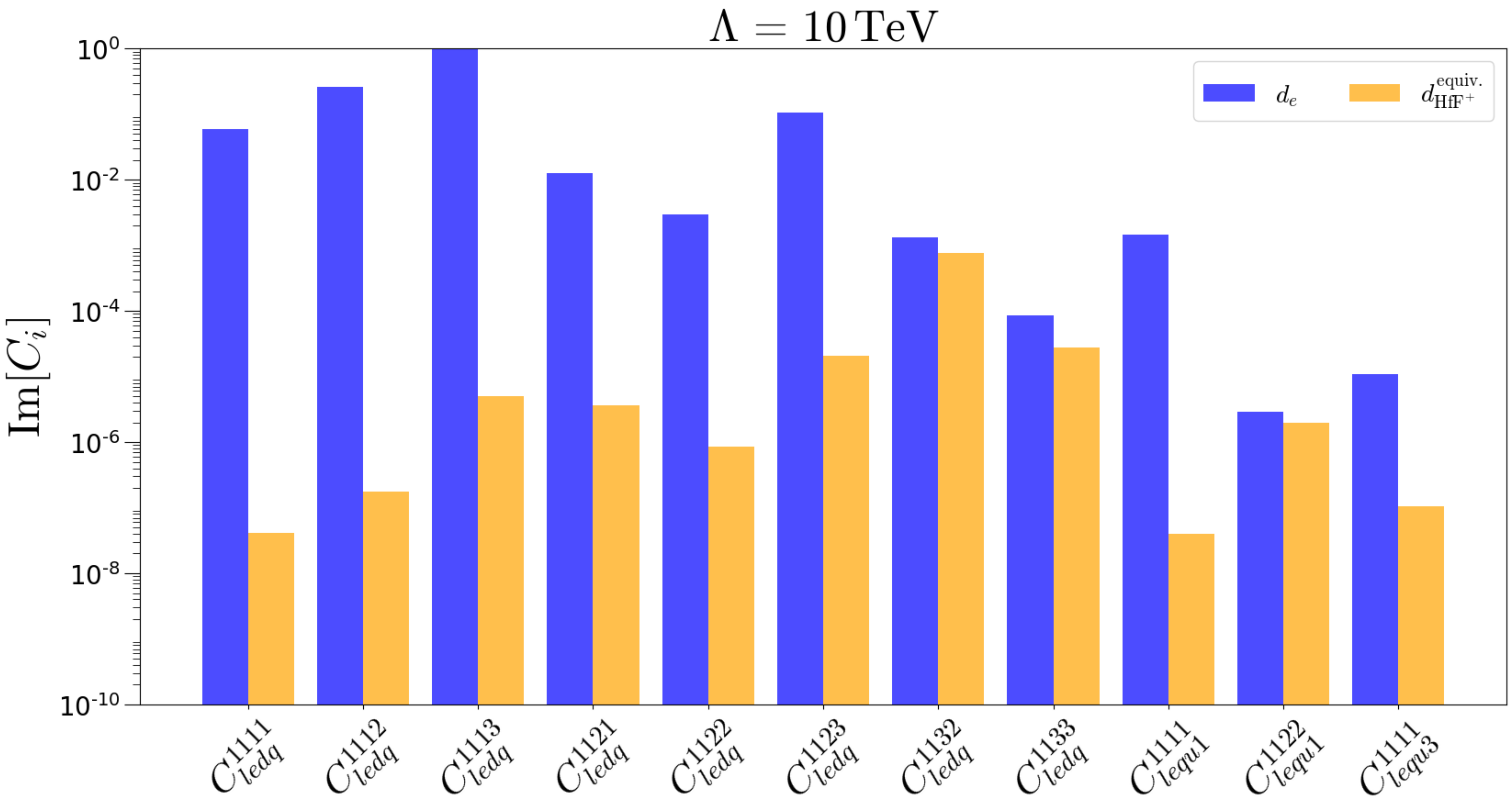
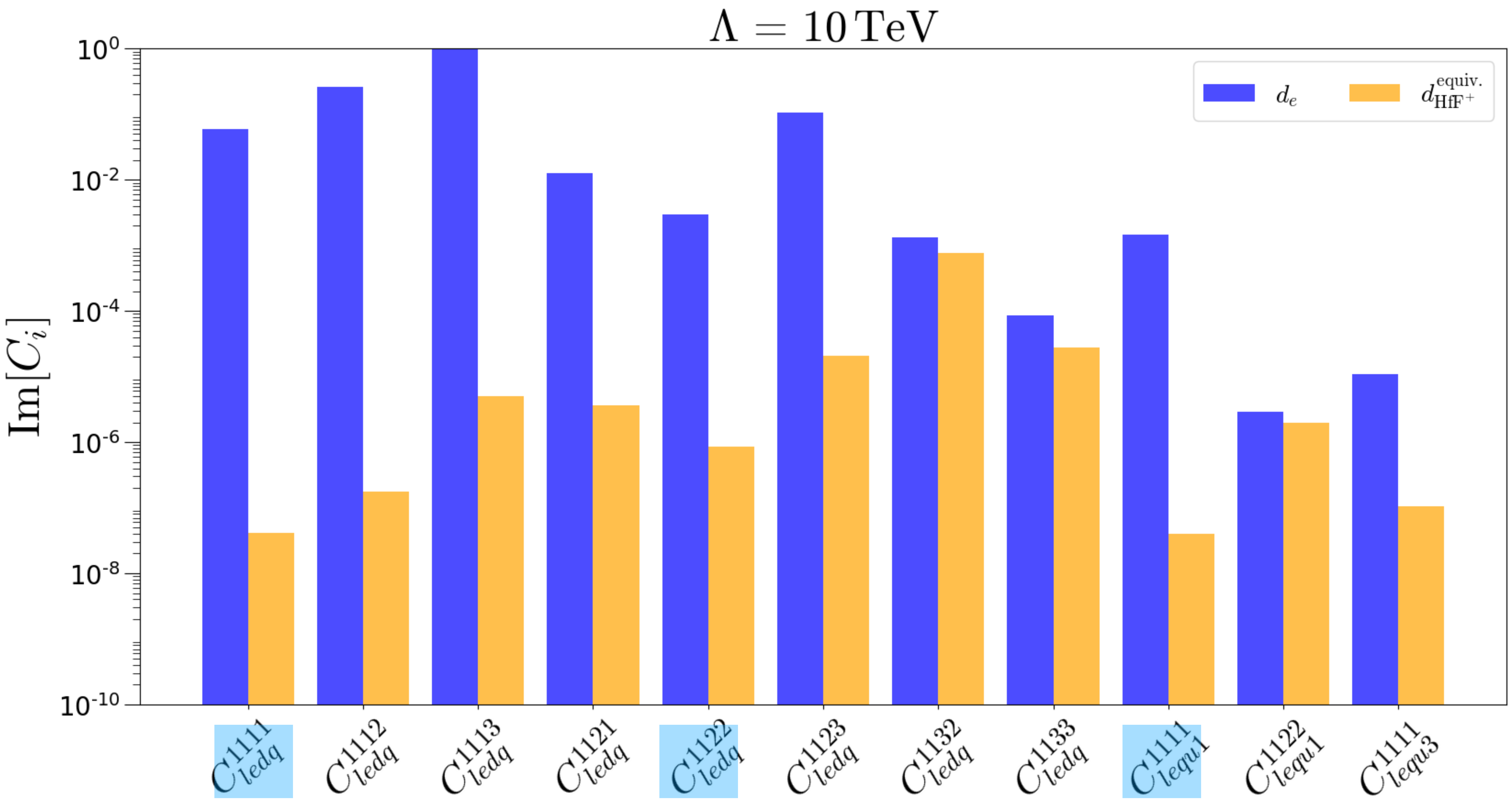


Running and matching:

Results II:

equivalent EDM is more sensitive than eEDM to some semileptonic operators



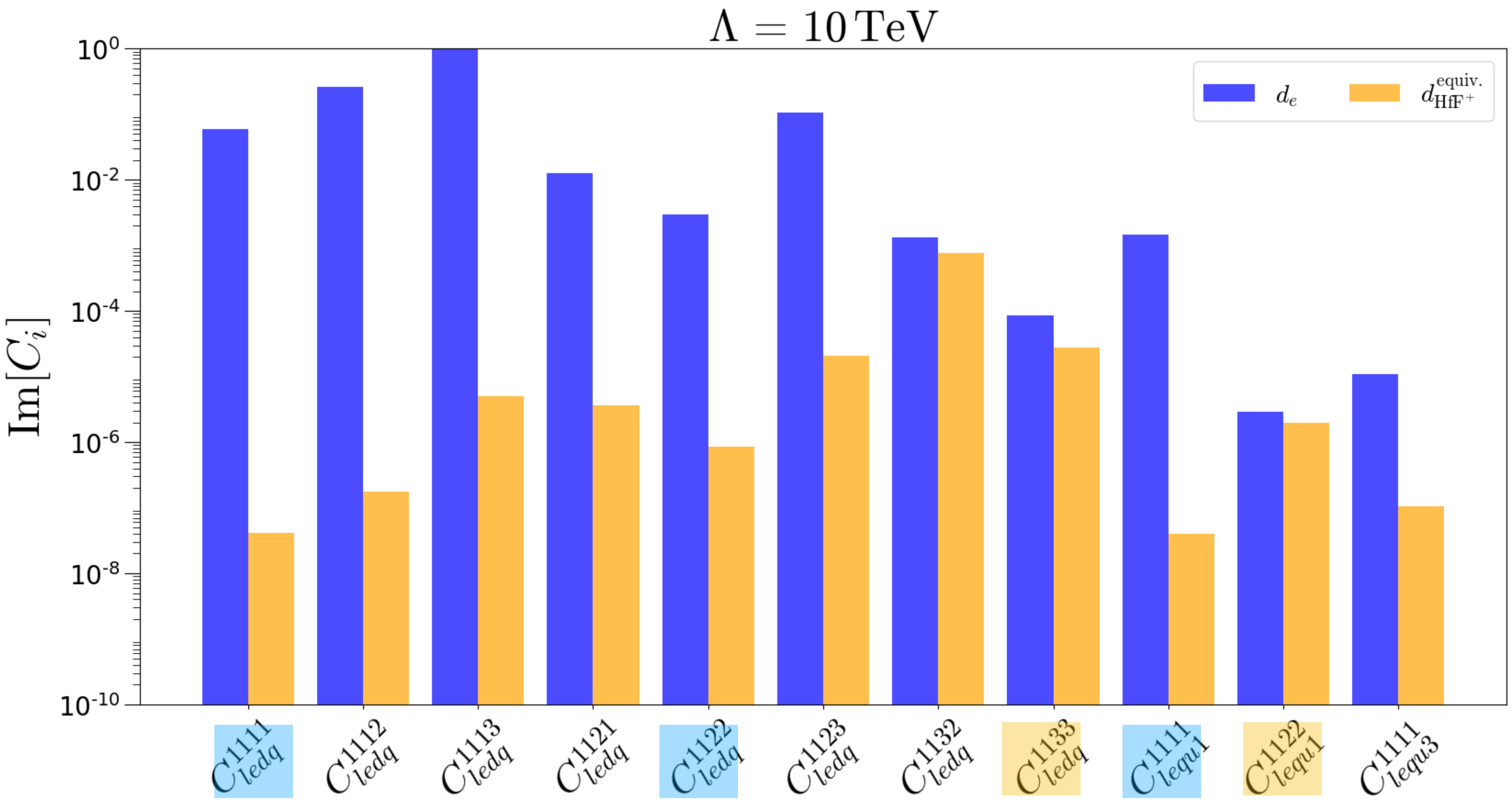
Running and matching:

Scalar:

- Light quarks contribution

Results II:

equivalent EDM is more sensitive than eEDM to some semileptonic operators



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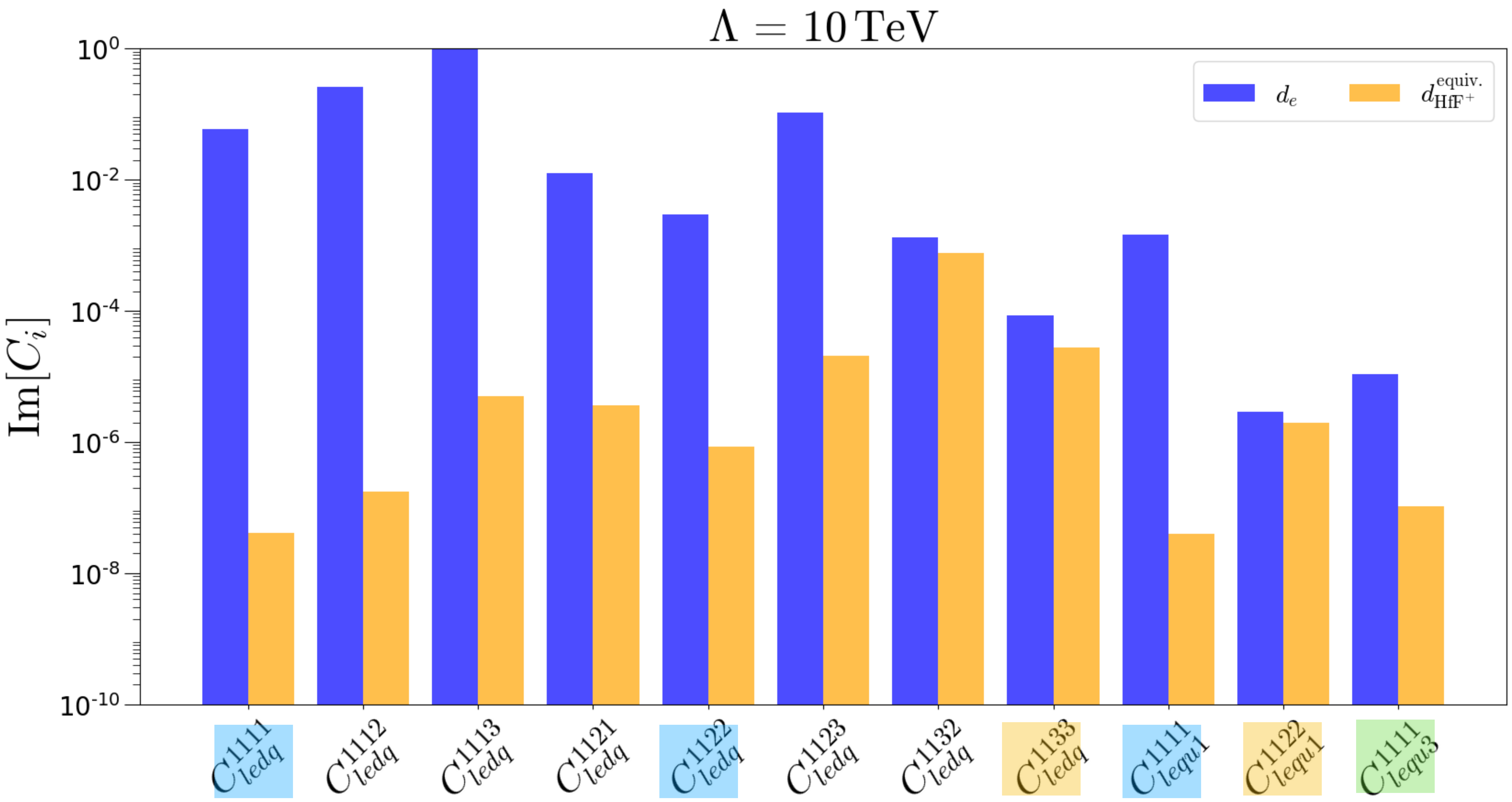


Running and matching:

Scalar:

- Light quarks contribution
- Heavy quarks contribution

1-loop mixing:

- Tensor-to-scalar with *u*

Conclusion

- *Electron dipole moment searches are conducted on atoms or molecules*
- *They are sensitive to a linear combination of eEDM and a semileptonic CP-odd int.*
- *Previous works focused just on eEDM sensitivity to SMEFT operators*

Results

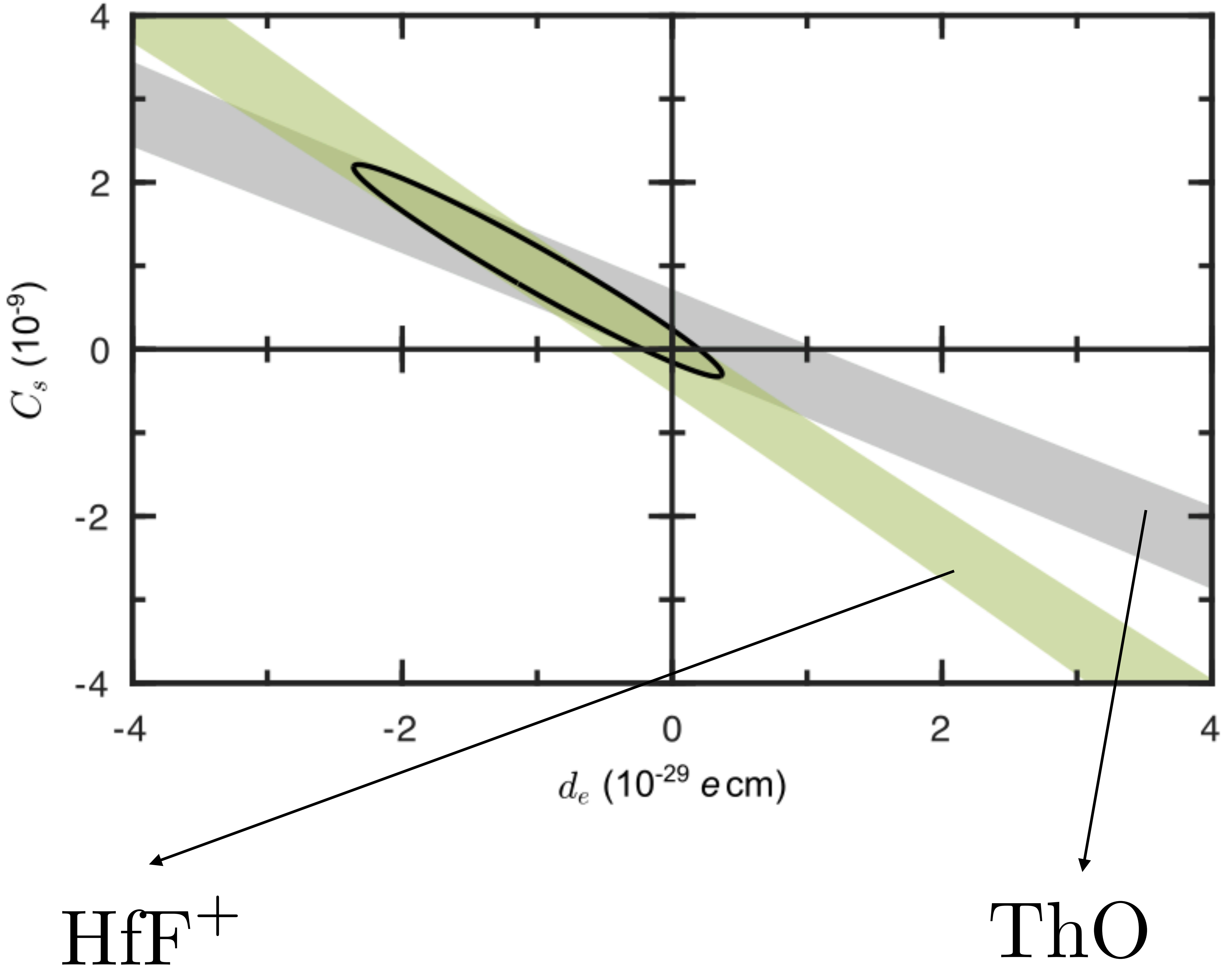
- *Extension of the analysis to explore the full direction probed by electron EDM exps.*
- *Sensitivities of the eEDM experiments to a larger classes of operators than previously recognized*

BACK UP

What if we have 2 or more Exps?

In EDM experiments I want to measure the energy shift when s is aligned with E
Compare to when is anti-aligned

Roussy et al.,hep-ph/2212.11841



$$hf = -2d_e E_{eff} + 2W_S C_S$$

$$d_{\rm sys}^{\rm equiv.} = d_e + \# C_S\, e \cdot cm$$

Two experiments with different #
Can disentangle eEDM and Cs.

$\mathrm{ThO} \sim 1.5 \times 10^{-20}$

$\mathrm{HfF}^+ \sim 0.9 \times 10^{-20}$

Combined fit

$|d_e| < 2.1 \times 10^{-29}$ e cm

$|C_S| < 1.9 \times 10^{-9}$

Matching at the nucleon scale

Non-perturbative matching at the confinement scale: connecting quark and gluons to Nucleons

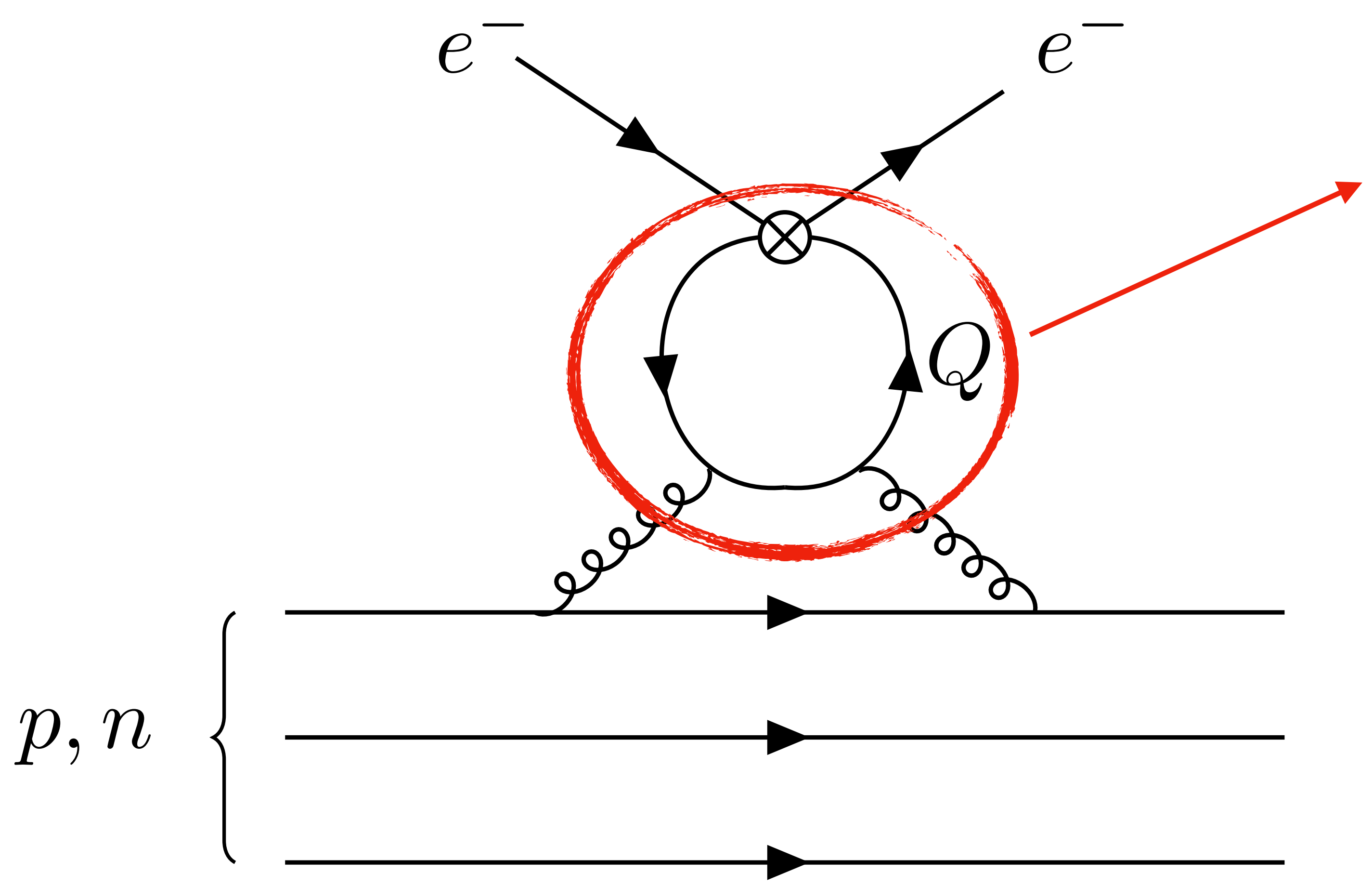
Relevant LEFT operators: $O^{eq}_{XY} = (\bar{e}P_X e)\,(\bar{q}P_Y q) \longrightarrow \frac{i}{2}\,\mathrm{Im}\,[C^{eq}_{RL} + C^{eq}_{RR}]\,(\bar{e}\gamma_5 e)(\bar{q}q) \equiv C^q_s(\bar{e}i\gamma_5 e)(\bar{q}q)$

Light quarks contribution:

$\langle\, N\,|\bar{q}q|\,N\,\rangle \sim G_S^{N,q}\langle\, N\,|\bar{N}N|\,N\,\rangle$

	$q=u$	$q=d$	$q=s$
$G_S^{p,q}$	9	8.2	0.42
$G_S^{n,q}$	8.1	9	0.42

Heavy quarks contribution:



One loop matching to $O_{eG} = (\bar{e}i\gamma_5 e)(G^a_{\mu\nu}G^{\mu\nu}_a)$

with

$$C_{eG} = -\frac{\alpha_s(m_Q)}{12\pi^2 m_Q}C^Q_s(m_Q)$$

$\downarrow$

$$\langle\, N\,|G^a_{\mu\nu}G^{\mu\nu}_a|\,N\,\rangle = -\frac{8\pi m_N}{9\alpha_s(\mu)}\langle\, N\,|\bar{N}N|\,N\,\rangle$$

Final expression matching Cs and semileptonic in LEFT:

$$\frac{\Lambda^2 G_F}{\sqrt{2}}C_S(\mu) = \sum_{q=u,d,s} G_s^{N,q}C^q_s(\mu) + \sum_{Q=c,b,t}\frac{2m_N}{27m_Q}C^Q_s(m_Q)$$

A bit of dipoles

Crucial for this work are the dipole operators at dimension 6

Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$

Spontaneous symmetry breaking and gauge boson eigenstates:

$$\varphi \to \begin{pmatrix} 0 & \frac{v+h}{\sqrt{2}} \end{pmatrix}^T$$

$$B_\mu = \cos\theta_w A_\mu - \sin\theta_w Z_\mu$$
$$W^3_\mu = \sin\theta_w A_\mu + \cos\theta_w Z_\mu$$

Matching to our Effective lagrangian: $\mathcal{L}_{EDM} = -\frac{i}{2} d\, \bar{f} \sigma_{\mu\nu} \gamma_5 f\, F^{\mu\nu}$

$$d_e(\mu) = \frac{\sqrt{2}v}{\Lambda^2} \mathrm{Im}\left[s_{\theta_W} C_{eW}(\mu) - c_{\theta_W} C_{eB}(\mu)\right]$$

But

Solution of RGE (SMEFT or LEFT):

$$\vec{C}(\mu_f) = \vec{C}(\mu_i) U(\mu_f, \mu_i)$$

→ Dipole operators at low energy can stem from the mixing under the RGE

Result I: some details

Leading log:

$$16\pi^2 \frac{dC_{eW}^{ij}}{d\ln\mu} = -2g_2 N_c C_{lequ(3)}^{ijlm} [Y_u]_{ml} - [Y_e^\dagger]_{ij} \Big(g_2 (C_{HW} + iC_{H\widetilde{W}}) + g_1 (y_l + y_e)(C_{HWB} + iC_{H\widetilde{W}B}) \Big)$$

$$16\pi^2 \frac{dC_{eB}^{ij}}{d\ln\mu} = 4g_1 N_c (y_u + y_q) C_{lequ(3)}^{ijlm} [Y_u]_{ml} - [Y_e^\dagger]_{ij} \Big(2g_1 (y_l + y_e)(C_{HB} + iC_{H\widetilde{B}}) + \frac{3}{2} g_2 (C_{HWB} + iC_{H\widetilde{W}B}) \Big)$$

Electron Yukawa Supressed

Heavy quarks Yukawa enhanced (especially top)

NLL:

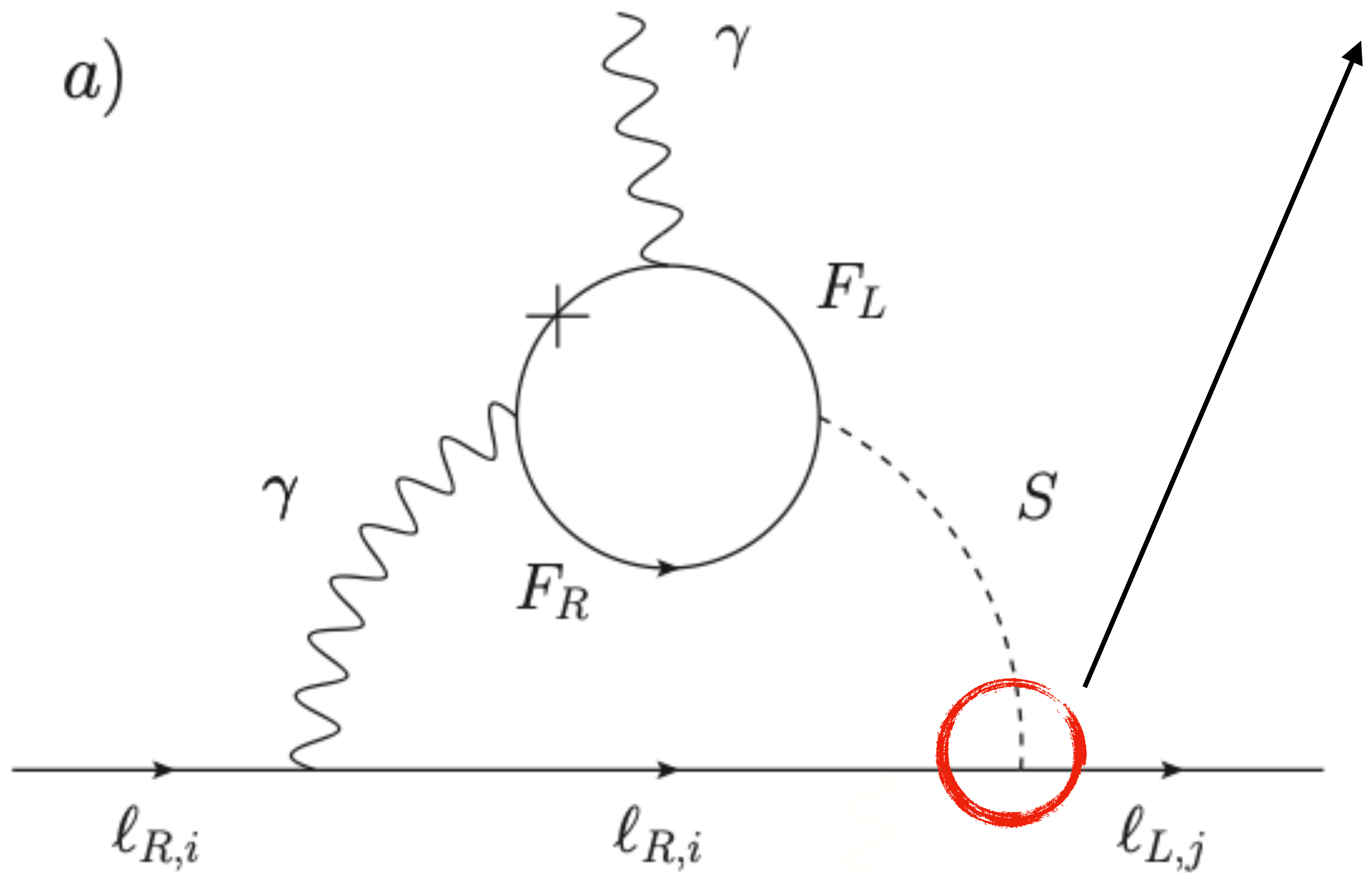
Most relevant effect from operators mixing with $C_{lequ(3)}^{ij33}$

$$\dot{C}^{(3)}_{\substack{lequ\\prst}} = +\frac{1}{8}\left(-4\left(\mathsf{y}_q + \mathsf{y}_u\right)\left(2\mathsf{y}_e - \mathsf{y}_q + \mathsf{y}_u\right) g_1^2 + 3g_2^2\right) C^{(1)}_{\substack{lequ\\prst}}$$

Flavor conserving scalar interaction.

Result I: Barr-Zee

Effects induced by modification of SM coupling

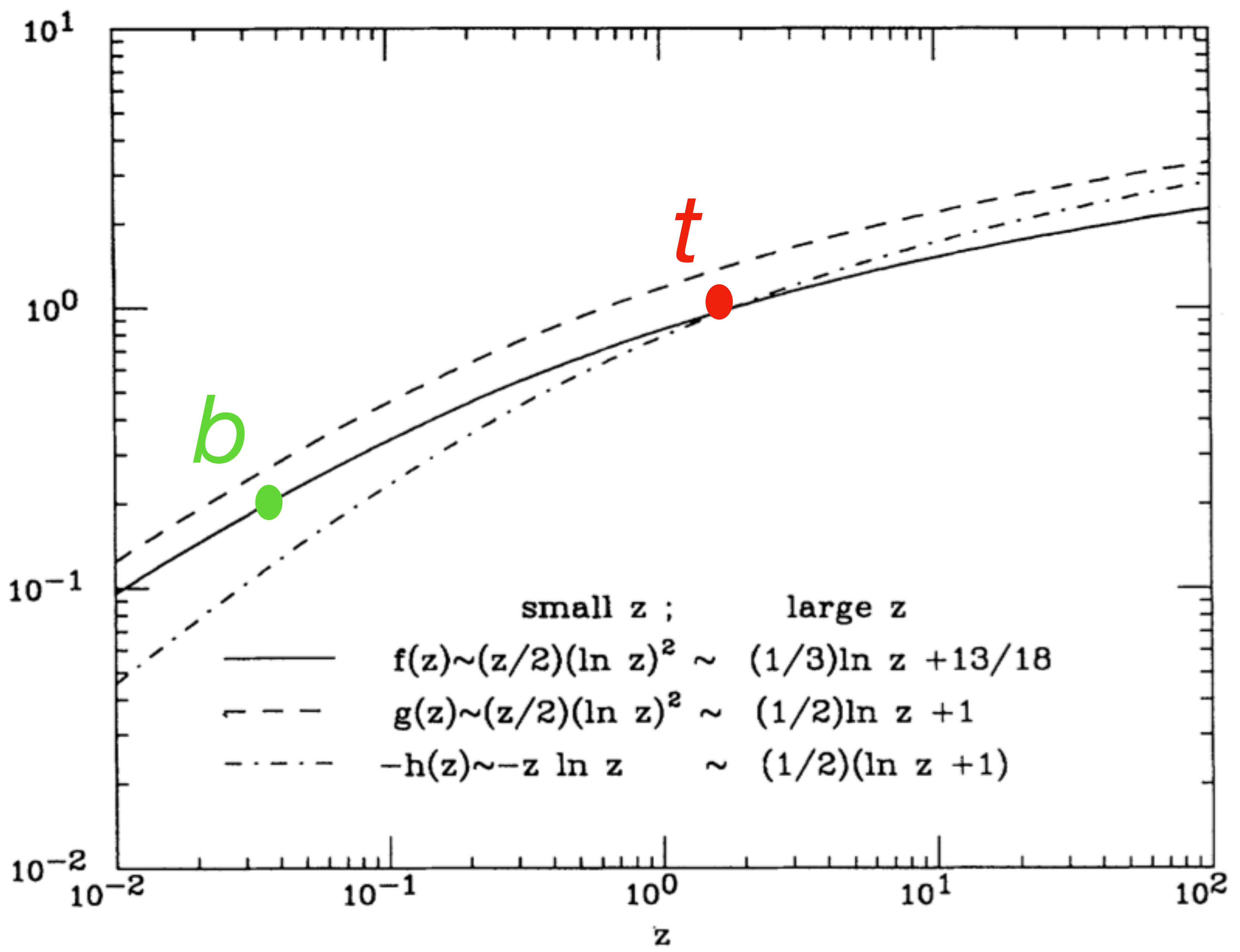


$\mathcal{O}^{ij}_{e\phi}$ can induce a modification between Higgs-fermions coupling → Yukawa couplings not proportional to the mass matrix

$$[\mathcal{Y}_\psi]_{rs} = \frac{1}{v_T}[M_\psi]_{rs}[1 + c_{H,\mathrm{kin}}] - \frac{v^2}{\sqrt{2}} C^*_{\substack{\psi H\\ sr}}$$

$$d_e \sim \frac{e\alpha}{4\pi^2}\frac{v}{\Lambda^2}\mathrm{Im}[C^{11}_{e\phi}]f(m_F/m_H)$$

SM fermion in the inner loop



Contribution with the W Boson in the loop are also relevant

Result II: Some details

Dominant effects in the in QCD running of scalar operator.

C_s dominates over d_e for almost all the semileptonic scalar interaction:

Exception: C_{lequ1}^{1133}
- Matching to Cs suppressed by $1/m_t$ ✗
- Mixing to the dipole at second order by enhanced by y_t ✓

One-loop mixing effect:

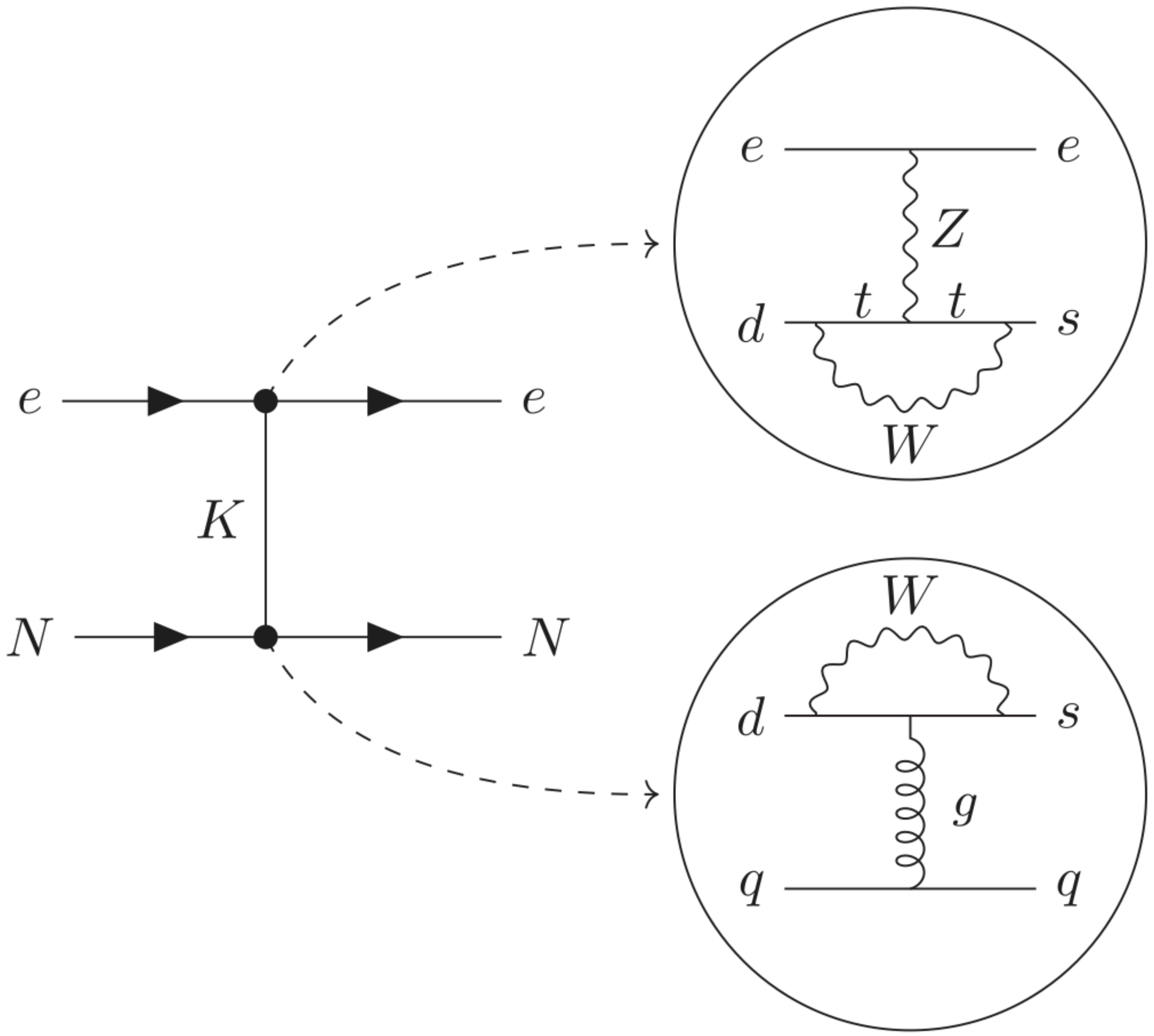
C_{lequ3}^{1111}
- Mixing to C_{lequ1}^{1111} at one loop via electroweak gauge boson exchange ✓
- Mixing to C_{eV}^{11} In the RGE at one loop with y_u suppression ✗
- Matching to C_{eV}^{11} non pert. ~ one order magnitude larger than RGE −

$$(\bar{e}_{Lp}\sigma^{\mu\nu}e_{Rr})(\bar{q}_L\sigma_{\mu\nu}q_R) \to -2Q_q e\,\Lambda_1\,(\bar{e}_{Lp}\sigma^{\mu\nu}e_{Rr})F^{\mu\nu} + \quad \Lambda_1 \sim c_T\frac{F_\pi^2}{\Lambda_\chi} = c_T\frac{\Lambda_\chi}{16\pi^2}$$

C_s contribution still dominant!

A closer look at the SM contribution

Leading contribution given by kaons exchange



$$\mathcal{L}_{Kee} = -2\sqrt{2} f_0 m_e \bar{e} i \gamma_5 e (K_S \times \mathrm{Im}\mathcal{P}_{\rm EW} + K_L \times \mathrm{Re}\mathcal{P}_{\rm EW})$$

$$\mathcal{P}_{\rm EW} = \frac{G_F}{\sqrt{2}} \times V_{ts}^* V_{td} \times \frac{\alpha_{\rm EM}(m_Z)}{4\pi \sin^2\theta_W} I(x_t)$$

$$\mathcal{L}_{KNN} \simeq -\frac{\sqrt{2} G_F \times [m_{\pi^+}]^2 f_\pi}{|V_{ud} V_{us}| f_0} \times 2.84(0.7\bar{p}p + \bar{n}n) \times (\mathrm{Re}(V_{ud}^* V_{us}) K_S + \mathrm{Im}(V_{ud}^* V_{us}) K_L).$$

$$C_S \simeq \mathcal{J} \times \frac{N + 0.7Z}{A} \times \frac{13[m_{\pi^+}]^2 f_\pi m_e G_F}{m_K^2} \times \frac{\alpha_{\rm EM} I(x_t)}{\pi \sin \theta_W^2}$$

$$C_S(\mathrm{LO+NLO}) \simeq 6.9 \times 10^{-16}$$

$$\Rightarrow d_e^{\rm equiv} \simeq 1.0 \times 10^{-35} \; e\,\mathrm{cm}.$$

$$\mathcal{J} = \mathrm{Im}(V_{ts}^* V_{td} V_{ud}^* V_{us}) \simeq 3.1 \times 10^{-5},$$